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Document downloaded from:

<http://hdl.handle.net/10459.1/67517>

The final publication is available at:

<https://doi.org/10.1016/j.still.2019.104488>

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**Tillage and irrigation system effects on soil carbon dioxide (CO₂) and methane (CH₄)
emissions in a maize monoculture under Mediterranean conditions**

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Abstract

Irrigation as well as soil tillage management are considered two possible strategies to reduce carbon dioxide (CO₂) and methane (CH₄) emissions from the soil in Mediterranean agroecosystems. The objective of this work was to assess the impact of the irrigation system (i.e. flood, F; and sprinkler, S) and the soil tillage system (i.e. conventional tillage, CT; no-tillage maintaining the maize stover, NTr; and no-tillage removing the maize stover, NT) on CO₂ and CH₄ emissions from the soil during three growing seasons (2015, 2016 and 2017) and two fallow periods between growing seasons (15-16 fallow and 16-17 fallow) in a maize (*Zea mays* L.) monoculture system. Soil temperature and water-filled pore space (WFPS) had a great influence on daily soil CO₂ fluxes but not on daily soil CH₄ fluxes. Daily soil CO₂ fluxes showed an increase with soil temperature in all tillage-irrigation treatments, especially when soil temperature was above 15°C, in coincidence with the maize plant growth. In contrast, soil WFPS differently affected daily soil CO₂ fluxes depending on the irrigation system. Under S irrigation, daily soil CO₂ fluxes increased with soil WFPS, whereas under F irrigation a threshold value of 60% WFPS was found, with a positive or negative effect on CO₂ fluxes for values below or above this threshold value, respectively. Over the three maize growing seasons, CT-S presented the greatest cumulative soil CO₂ emissions with a seasonal average value of 3.28 Mg CO₂-C ha⁻¹. In contrast, for the same period, NTr-S cumulative soil CO₂ emissions were up to 42% lower than the CT-S cumulative soil CO₂ emissions. Cumulative CH₄ emissions were only affected by soil tillage during the 16-17 fallow period, observing greater net CH₄ uptake under NTr and NT compared with CT. This work highlights the importance of irrigation and soil tillage systems as key agricultural practices to minimize soil CO₂ and CH₄ emissions under Mediterranean conditions.

39 **Keywords**

40 Soil CO₂ emissions; soil CH₄ emissions; sprinkler irrigation; flood irrigation;
41 conventional tillage; no-tillage; maize monoculture; maize stover

42 **Abbreviations**

43 CIR, crop irrigation requirement; ETo, reference evapotranspiration; ETc, crop
44 evapotranspiration; WFPS, water-filled pore space

45

1. Introduction

Mediterranean climate is characterized by low and erratic precipitations, mainly occurring during autumn and spring, being irrigation water supplies necessary for most summer crops. On the other hand, in Mediterranean areas, adequate selection and performance of agricultural management practices such as irrigation and tillage may help to mitigate greenhouse gas (GHG) emissions from agricultural soils (Sanz-Cobena *et al.*, 2017).

In Mediterranean agriculture, irrigation acreage is increasing due to the higher crop yields in irrigated cropping systems compared with rainfed farming systems. Sprinkler and flood irrigation systems are the most used worldwide. In turn, the acreage under sprinkler irrigation is increasing compared with flood irrigation due not only to higher crop yields but also to better automation of the irrigation process and to a reduction of runoff and drainage since irrigation water is applied at low rates (Rawlins and Raats, 1975; Playán and Mateos, 2006; Lecina *et al.*, 2010). Moreover, irrigation systems, given their capacity to modify the soil water content, directly affect the soil carbon cycle through an increase of net primary productivity and soil microbial activity, which usually results in an increase of soil organic carbon (SOC) content and an impact on the factors controlling the production and transport of CO₂ and CH₄ in the soil (Wu *et al.*, 2008; Aguilera *et al.*, 2013; Trost *et al.*, 2013).

Likewise, soil tillage can have an impact on soil CO₂ and CH₄ emissions by affecting the SOC evolution and soil physical properties like soil structure involved in the production/consumption and transport of these gases through the soil profile (West and Post, 2002; Ball, 2013). In Mediterranean areas, no-tillage leads to an increase of SOC levels due to the physical protection of carbon within soil aggregates, which, at the same time, results in a better soil structure (Álvarez-Fuentes *et al.*, 2008; Follett *et al.*, 2013;

Plaza-Bonilla *et al.*, 2014). In contrast, tillage promotes the oxidation of soil organic matter by microbial activity due to the direct incorporation of the crop stover, the disturbing and mixing of the soil profile and the breakdown of soil aggregates, which results in more favourable conditions for decomposition of the soil organic matter by soil microorganism (Paustian *et al.*, 1997). Moreover, crop stover management can influence CO₂ and CH₄ emissions from the soil. Thus, maintaining the crop stover on the soil surface can reduce soil water losses by evaporation, while removing it can lead to a reduction in the SOC content, thus resulting in a degradation of soil physical properties (Sauer *et al.*, 1998; Blanco-Canqui and Lal, 2008).

Soil CO₂ production is driven by abiotic and biotic processes. The main abiotic processes involved in the soil CO₂ production is the dissolution of inorganic forms of carbon like carbonates (CO₃²⁻) (Ramnarine *et al.*, 2012; Rey, 2015). The soil CO₂ coming from biotic processes is a consequence of root respiration and microbial decomposition of organic matter and is regulated by soil temperature and water content (Linn and Doran, 1984; Lloyd and Taylor, 1994; Davidson and Janssens, 2006). Moreover, soil may act as a sink or as a source of CH₄, depending on the O₂ availability for microbial activity. Hence, soil methanogenesis (production of CH₄) requires strict anaerobiosis and low oxidation-reduction potentials (Eh). In contrast, soil methanotrophy (consumption of CH₄) need high Eh values and the presence of O₂, being the latter the main limiting factor for soil methanotrophy (Hütsch, 2001; Le Mer and Roger, 2001). Accordingly, irrigation and tillage practices may affect the production and dynamics of CO₂ and CH₄ in the soil by modifying the soil water-filled pore space (WFPS), soil temperature and soil structure. These variables control the microbial activity, influence the crop development and affect the diffusivity and transport of gases throughout the soil profile (Linn and Doran, 1984; Wang *et al.*, 1993; Ball *et al.*, 1999; Smith *et al.*, 2003; Ball *et al.*, 2008).

Currently, the available information about the effects of different irrigation systems and the interaction between tillage and irrigation on soil CO₂ and CH₄ emissions under Mediterranean conditions is scarce. Several studies have been carried out under Mediterranean conditions to assess the influence of different tillage practices, different types and doses of N fertilizers or the use of cover crops on CO₂ and CH₄ emissions from the soil (Álvaro-Fuentes *et al.*, 2008; Menéndez *et al.*, 2008; Meijide *et al.*, 2010; Morell *et al.*, 2011; Plaza-Bonilla *et al.*, 2014; Sanz-Cobeña *et al.*, 2014). All these studies, however, were carried out under rainfed conditions. In irrigated conditions, some researches have been conducted to find out the effect of different tillage systems and irrigation management on soil CO₂ and CH₄ emissions (Zornoza *et al.*, 2016; Forte *et al.*, 2017; Maris *et al.*, 2018; Pareja-Sánchez *et al.*, 2019), but none of them took into consideration the interaction between tillage and irrigation systems.

The present study was aimed to evaluate the effects of soil tillage systems (conventional tillage vs. no-tillage) and irrigation systems (sprinkler vs. flood irrigation) on soil CO₂ and CH₄ emissions under maize cultivation in a Mediterranean agroecosystem. We hypothesize that irrigation system and soil tillage management would impact on the soil carbon cycle by modifying soil physical properties, soil moisture content and SOC contents, which would also affect the soil CO₂ and CH₄ emissions. In particular, we hypothesize that conventional tillage under sprinkler irrigation would result in greater CO₂ emissions due to the expected higher crop productivity of this irrigation system and the higher soil aeration associated with tillage. Likewise, we hypothesize that flood irrigation would enhance soil CH₄ production since, under this irrigation system, anaerobic conditions would occur after each irrigation event.

2. Material and Methods

2.1 Site description and experimental design

The experiment was established in 2015 at Zaragoza, Spain (41° 42' N, 0° 49' W, 225 m altitude). The climate in the area is Mediterranean semiarid with an annual mean air temperature of 14.1 °C, an annual precipitation of 298 mm and a grass reference crop evapotranspiration (ET_o) of 1243 mm. The soil is a Typic Xerofluvent (Soil Survey Staff, 2015). The main properties of the experimental soil are given in Table 1.

On the experimental site, winter wheat (*Triticum aestivum* L.) followed by maize (*Zea mays* L.) as second crop was grown under conventional tillage and flood irrigation during the last ten years prior to the establishment of the experiment. Accordingly, winter wheat was the precedent crop in the experimental field. In 2015, the experimental field (0.83 ha) was divided in two identical areas, one for flood irrigation (F) and the other for a hand-move sprinkler irrigation system (S). At the same time, three soil tillage systems (i.e. conventional tillage, CT; no-tillage maintaining the maize stover, NTr; and no-tillage removing the maize stover, NT) were also established in each of the two areas with different irrigation system. The experimental design was a split-block with three replications and a plot size of 6 x 18 m.

One pass of a subsoiler to 30 cm depth followed by one pass of a disk harrow in winter and one pass of a rotary tiller just before sowing were performed in the CT treatment. No-tillage treatments consisted of an application of glyphosate (36% at 5L ha⁻¹) to control weeds before sowing. Maize cv. Pioneer P1785 was sown in rows 75 cm apart at a planting density of 89,500 plants ha⁻¹ (Table 2).

Fertilization was the same in all treatments and consisted of one application of 800 kg ha⁻¹ of NPK 8-15-15 compound fertilizer (ammonium N (N-NH₄); phosphorus P(P-
P₂O₅); potassium K (K-K₂O)) before planting and one top dressing application of 740 kg ha⁻¹ of calcium ammonium nitrate 27% N (13.5% ammonium N (N-NH₄) – 13.5% nitrate N (N-NO₃)) at V6-V8 maize growth stage. Harvest was done with a commercial combine (Table 2). Afterwards, the stover was chopped and spread over the soil by a chopper machine. After harvest of the first maize growing season (2015), maize stover was manually removed from the NT treatment plots. Therefore, the NT treatment started the second growing season (2016) after the first fallow period (15-16 fallow). It is important to state that during the two fallow periods between the three maize growing seasons no crop was grown. Weed and pest control was done according to best management practices in the area.

Meteorological data from a weather station 1km far from the field experiment was used to obtain daily reference evapotranspiration (ET_o) using the FAO Penman-Monteith method (Allen *et al.*, 1998). The crop coefficient (K_c) for maize was calculated as a function of thermal time using an equation developed at the same location of the experiment (Martínez-Cob *et al.*, 2008). Daily maize crop evapotranspiration (ET_c) was then obtained by multiplying ET_o by K_c (Allen *et al.*, 1998). Crop irrigation requirements (CIR) were determined weekly by subtracting the effective precipitation (75% of total weekly precipitation) from ET_c and considering an irrigation efficiency of 85% (Dastane, 1978) (Table 3). Irrigation frequency differed between irrigation systems. Hence, in the S system, two irrigation events per week were performed (i.e. on Monday and Wednesday). In the F system irrigation occurred every 10-14 days. In order to favour plant emergence and to avoid differences in plant density among treatments, irrigation

water was applied by sprinkler irrigation to all the plots until V6 growth stage. For each irrigation system, the same amount of irrigation water was applied to all tillage treatments.

2.2 Gas measurements

Soil CO₂ and CH₄ emissions were measured from April 2015 to October 2017 using the closed chamber technique (Hutchinson and Moiser, 1981). Two polyvinyl chloride (PVC) rings (31.5 cm internal diameter) per plot were inserted 10 cm into the soil on April 2015 and were only removed at tillage, planting and harvesting operations. Each PVC chamber (20 cm height) was covered with a reflective layer of aluminium film to avoid increases of the internal temperature, which was measured by introducing thermometers before the chambers were closed.

Soil gas sampling frequency was weekly from planting (April) until maize milk stage (R3) (mid-August), every two weeks from mid-August until harvest (late September) and every three weeks during the fallow period (November-March). Moreover, soil gas sampling frequency was increased for tillage, fertilization and flood irrigation events. During tillage operations, soil gas samplings were performed 24 h before and 24 and 96 h after tillage, while for fertilization operations soil gas samples were taken 24 h before and 24, 48, 72, 96, 144 and 192 h after fertilization. Finally, for every flood irrigation event soil gas sampling frequency consisted of one sampling just before applying the irrigation water and several samplings (3-4) during the five days following the irrigation event. In the case of S irrigation, gas sampling was performed between the two weekly irrigation events.

In each soil gas sampling, 20 mL of gas were collected at 0, 20 and 40 min after chamber closure and transferred to an evacuated 12-mL Exetainer ® borosilicate glass vial (model 038W, Labco, High Wycombe, UK). On every sampling date, a total of 54 gas samples were collected for each irrigation system (9 plots x 2 observations per plot x

3 sampling times per chamber). The concentration of CO₂ and CH₄ were measured with a gas chromatograph system (Agilent 7890B, Agilent, Santa Clara, CA, United States) equipped with a flame ionization detector (FID) coupled to a methanizer for determining CO₂. The system was calibrated using ultra-high purity CO₂ and CH₄ standards (Carbueros Metálicos, Barcelona, Spain). Further details of the analysis method are described elsewhere (Franco-Luesma *et al.*, 2019). Mass-based emission rates of each gas were calculated by the linear increase of the particular gas concentration inside the chamber during the enclosure time and correcting it by the internal air chamber temperature.

2.3 Soil and crop aboveground biomass measurements

Soil temperature (at 5 cm depth) and soil water content (0-5 cm) were measured using a TM 65 probe (Crison, Carpi, Italy) and a GS3 probe (Decagon Devices, Pullman, WA), respectively. Soil bulk density (0-5 cm) was determined once per month using the cylinder method (Grossman and Reinsch, 2002); stainless steel cylinders 5 cm in length and 8 cm in diameter were used to collect undisturbed soil samples. Soil water filled pore space (WFPS) was calculated from the volumetric soil water content and the soil bulk density measurements, assuming a soil particle density of 2.65 Mg m⁻³.

Maize aboveground biomass was determined manually before the combine harvest by cutting the maize plants of three 2-m maize rows, at the soil surface level, at two randomly selected locations per plot. A sub-sample of four entire plants was taken. The cobs were separated, and both cobs and the rest of the plant were oven-dried at 60° C for 48 h and weighed. Afterwards, the dry weight of the plant and the cob were summed to obtain the total maize aboveground biomass.

2.4 Data analysis

Cumulative soil CO₂ and CH₄ emissions for each treatment and measurement period: 2015, 2016 and 2017 maize growing seasons (April – October) and 15–16 and 16–17 fallow periods (November – March) were expressed on a mass basis (i.e., Mg C-CO₂ ha⁻¹; g C-CH₄ ha⁻¹) using the trapezoid rule (Levy *et al.*, 2017). Data normality was checked by the Shapiro-Wilk test and when necessary, data were transformed to get a normal distribution. Sqrt-transformation for daily soil CO₂ fluxes and logarithm transformation for cumulative soil CO₂ emissions were needed to comply with normality. Transformed daily soil CO₂ fluxes, daily soil CH₄ fluxes, WFPS, and soil temperature were analysed separately for each measurement period (i.e. 2015, 2016, 2017 maize growing seasons and 15-16, 16-17 fallow periods) and each irrigation system, sprinkler and flood irrigation, through repeated measures analysis of variance (ANOVA), with soil tillage system, date of sampling and their interactions as sources of variation. In addition, different ANOVA analyses for each measurement period were performed for transformed cumulative soil CO₂ emission values, cumulative soil CH₄ emissions and maize aboveground biomass, with irrigation system, soil tillage system and their interactions as sources of variation. When significant, differences between treatments were identified at 0.05 probability level using the Tukey test. Simple regressions between CO₂ fluxes, CH₄ fluxes, WFPS and soil temperature were performed to test the presence of significant relationships. All statistical analyses were performed with JMP 10 statistical package (SAS Institute Inc., 2012).

3. Results

3.1 Weather conditions, soil WFPS and soil temperature

Daily mean air temperature, precipitation and ETo were recorded for the entire measurement period. Air temperature and ETo values showed an increase from April until maximum values in July and August and then a decrease reaching the lowest values in January and February (Figure 1). Over the three maize growing seasons, average daily air temperature was 20.6, 19.9 and 20.5°C for 2015, 2016 and 2017, respectively, while during the 15-16 and 16-17 fallow periods, daily air temperature was 9.2 and 9.1°C, respectively. Likewise, a total precipitation of 116, 167 and 151 mm was recorded in 2015, 2016 and 2017 maize growing seasons, respectively, while total precipitation during fallow was 180 and 272 mm for the 15-16 and 16-17 fallow periods, respectively.

For both irrigation systems and throughout the entire measurement period, the WFPS was significantly affected by the interaction between tillage and sampling date (Table 4). In addition, during the irrigation period (June – September), F irrigation presented large fluctuations of WFPS, with increases from 30 to 100% WFPS in less than 24h, which returned to values close to 30% WFPS in less than 5 days after the irrigation event. However, S irrigation presented a lower temporal variation of WFPS, with values ranging from 30 to 60% through the irrigation period (Figure 2). On average, for the three maize growing seasons, mean CT-WFPS values were 38 and 55% for S and F irrigation, respectively, whereas, mean NTr- and NT-WFPS values were 58 and 64%, and 50 and 58% for S and F irrigation, respectively.

Soil temperature was significantly affected by the interaction between tillage and sampling date during all measurement periods except during the 15-16 fallow for S irrigation (Table 4). Over the three maize growing seasons, mean soil temperature (at 5

cm depth) was 19.7 (2015), 17.7 (2016) and 18.2°C (2017) in S irrigation and 19.4 (2015), 18.9 (2016) and 19.2°C (2017) in F irrigation (Figure 3).

3.2 Carbon dioxide emissions

For both irrigation systems, daily soil CO₂ fluxes were affected by tillage, sampling date and their interaction (Table 5). During the three maize growing seasons and under both irrigation systems, soil CO₂ fluxes showed a similar pattern, with an increase in the emission rates concomitant with the crop growth over the maize growing season and reaching the maximum values in July coinciding with maize tasseling stage (VT) (Figure 4). Once soil CO₂ fluxes reached this peak, they started to decrease presenting the lowest values during the fallow periods (November – March) (Figure 4).

In the three growing seasons and under S irrigation, CT showed greater daily soil CO₂ fluxes than NT and NTr, with mean daily values of 2.50, 1.53 and 1.75 g CO₂-C m⁻² day⁻¹ for 2015, 2016 and 2017, respectively. However, under F irrigation, differences among tillage systems were only found in the 2017 growing season when CO₂ fluxes were greater under CT than under NT (Table 5).

Over the entire experimental time, daily soil CO₂ fluxes and soil temperature at 5cm depth presented a significant positive exponential relationship for both irrigation systems and the three tillage systems (Figure 5). According to these relationships, when soil temperature was below to 15° C (mostly during the fallow periods) the response of daily soil CO₂ fluxes for the six treatments showed a linear behaviour. However, when soil temperature values were above 15° C (mostly during the growing season period) daily soil CO₂ fluxes increased rapidly with soil temperature increase. Moreover, soil temperature showed a trend to a greater impact on soil CO₂ fluxes under S irrigation than

under F irrigation, with an increment in the slope value of 24, 20 and 33% for CT, NTr and NT, respectively (Figure 5).

Daily soil CO₂ fluxes presented a significant linear relationships with soil WFPS (Figure 6). For each irrigation system, different trends were observed, with positive increases of soil CO₂ fluxes with soil WFPS in all three tillage systems under S irrigation. Under F irrigation, all tillage systems also showed a linear positive increase of daily soil CO₂ fluxes with soil WFPS but only until a threshold value of 60% WFPS. From 60 to 100% WFPS, soil CO₂ fluxes linearly decreased as soil WFPS increased (Figure 6).

Throughout the three maize growing seasons, cumulative CO₂ emissions were significantly affected by the interaction between tillage and irrigation system (Table 6). In all three growing seasons, cumulative soil CO₂ emissions in the CT-S treatment were greater than in the other tillage-irrigation treatments (Figure 7). Moreover, for both fallow periods, cumulative soil CO₂ emissions showed significant differences between tillage systems (Table 6). Over the two fallow periods, NT presented lower mean cumulative emissions values (0.52 and 0.54 Mg CO₂-C ha⁻¹ in the 15-16 and 16-17 fallow periods, respectively) compared with CT and NTr tillage (0.77 and 0.75 Mg CO₂-C ha⁻¹ in CT and 0.85 and 0.85 Mg CO₂-C ha⁻¹ in NTr, for 15-16 and 16-17 fallows, respectively) (data not shown).

3.3. Methane emissions

In the three maize growing seasons and the two fallow periods, no significant differences were observed for daily soil CH₄ fluxes among tillage systems (Table 5). Daily soil CH₄ fluxes ranged between -1.00 and 1.00 mg CH₄-C m⁻² day⁻¹ during most of the experimental time without presenting any clear pattern of CH₄ emission or consumption.

Cumulative soil CH₄ emissions were only affected by tillage during the 16-17 fallow period (Table 6), showing NTr lower cumulative CH₄ emissions compared with CT and NT, with mean cumulative values of -400, -91 and -106 g CH₄-C ha⁻¹ for NTr, CT and NT, respectively (data not shown).

3.4. Maize aboveground biomass

Over the three growing seasons, maize aboveground biomass was significantly affected by the interaction between irrigation system and tillage (Table 6). Thus, while the NTr-S treatment showed greater maize aboveground biomass values than NTr-F in 2015, in 2017 the same treatment presented greater maize aboveground biomass compared with NT-S and with NTr and NT under F irrigation. In 2016, CT resulted in higher maize aboveground biomass values compared with NT and NTr under both irrigation systems (Figure 9). In addition, a positive linear relationship was observed between cumulative soil CO₂ emissions and total maize aboveground biomass for each of the three maize growing seasons (Figure 10).

4. Discussion

Overall, the results obtained in our three maize growing seasons field experiment showed that tillage and irrigation system due to their capacity to modify soil water content and soil temperature had a significant impact on soil CO₂ emissions but not on CH₄ emissions. Likewise, carbonate dissolution is one of the main abiotic processes that can contribute to the CO₂ emissions from the soil in this semiarid climate. However, our study was focused on the biologically-derived C emissions.

Daily soil CO₂ fluxes presented a temporal pattern similar to that observed by Franco-Luesma *et al.* (2019) and Pareja-Sánchez *et al.* (2019) for irrigated maize fields under Mediterranean conditions. This temporal evolution of soil CO₂ fluxes was characterized by low values during the fallow period, followed by a rapid increase of the emissions concomitant with the growth of the maize crop and reaching maximum values at the maize tasseling stage (VT) to decrease afterwards until the fallow period when the lowest values were measured.

This soil CO₂ flux pattern found during the maize growing season was partially explained by the effect of soil temperature, as it was demonstrated by the positive relationship found between these two variables as it has also been reported previously (Howard and Howard, 1993; Lloyd and Taylor, 1994; Fang and Moncrieff, 2001). The different response of soil CO₂ fluxes over the different periods (fallow vs growing season) was related with the combined effects of soil temperature and the presence of a crop and its growth that regulate the CO₂ emissions from the soil (Davidson and Janssens, 2006). Thus, the greater soil temperature, the root-derived CO₂ and the increase of C sources coming from the root exudates would have led to better conditions for the production of CO₂ in the soil during the growing season period than over the fallow period, when there

are not root-derived CO₂ and colder temperatures can affect soil biological processes by the deactivation of enzymes (Sharpe & De Michelle 1977; Rochette and Flanagan, 1997).

Soil WFPS also affected soil CO₂ fluxes but with different response depending on the irrigation system. Hence, under F irrigation, soil CO₂ fluxes increased with WFPS up to 60% value but from this WFPS value onwards soil CO₂ fluxes decreased. In our soil conditions, this value of 60% WFPS is usually coincident with the field capacity point. Moreover, the 60% WFPS has been identified as a threshold for microbial activity since values higher than 60% WFPS lead to a reduction of the O₂ availability in soils and, thus, to a decrease of soil microorganism activity, one of the main processes involved in the production of CO₂ in soils (Linn and Doran, 1984). Under F irrigation, large amounts of water (from 80 to 100 mm) was applied in each irrigation event. These large additions of water usually increase WFPS to values above 60% during the following four days after the irrigation event. In contrast, S irrigation resulted in steady soil WFPS values (about 50-60%) over the growing season, which were close to the optimum WFPS values for microorganism activity (Linn and Doran, 1984) and, thus, contributing to the greater soil CO₂ fluxes found in S irrigation compared with F irrigation.

Cumulative soil CO₂ emissions measured in this work were similar to those reported by Forte *et al.* (2017) who compared the effects of minimum tillage (rotary harrow) and conventional tillage (mouldboard ploughing to 30 cm depth) on soil CO₂ emissions under irrigated maize in Campania (southern Italy). In our work, over the three maize growing seasons, S irrigation increased cumulative soil CO₂ emission by 24% compared with F irrigation. This increase of cumulative soil CO₂ emissions under S irrigation can be related with the effect of the irrigation system on soil WFPS, as explained before, but also with the effect of the total maize aboveground biomass on cumulative soil CO₂ emissions since maize root respiration can account for about 50% of the total soil respiration during

the maize vegetative stages (Rochette and Flanagan, 1997). Thus, a positive impact of maize aboveground biomass on soil CO₂ emissions, as well as the linear increase of soil respiration with WFPS observed under S irrigation, could explain the higher cumulative soil CO₂ emissions measured under this irrigation system.

Throughout the three maize growing seasons, S irrigation increased by 10% the maize aboveground biomass compared with F irrigation. Segal *et al.* (2006), in a lysimeter study carried out at Arava research station (Arava Valley, Israel), observed increments of ornamental sunflower yields when the irrigation frequency was increased. In general, higher irrigation frequency results in greater soil water content and higher water potential in the root zone favouring plant water uptake. Consequently, in our study, the higher irrigation frequency in S irrigation compared with F irrigation (two times per week under S irrigation vs one time every 10 days under F irrigation) led to a relatively steady high WFPS levels in S irrigation during the growing season, which contributed to attain high crop yields. On the other hand, Ren *et al.* (2016) observed negative impacts on maize growth when water was maintained above the soil surface for 3 or 6 days. In our study, water above the soil surface was observed under F irrigation at least during the first 24h after the irrigation event. Then, WFPS started to decrease rapidly reaching values lower than 30%, which probably resulted in lower plant water uptake due to a lower water potential in the root zone. These facts would explain the lower aboveground biomass obtained in the F irrigation system compared with S irrigation.

In addition, CT increased cumulative soil CO₂ emissions by 21 and 39% compared with NTr and NT, respectively. The direct incorporation of the maize stover into the soil by tillage operations could increase the availability of C for soil microorganisms, thus increasing CO₂ production. This result is in agreement with the findings reported by Alluvione *et al.* (2009) in a similar experiment comparing conventional tillage and no-

tillage in an irrigated maize monoculture. Moreover, several studies (e.g. Blanco-Canqui and Lal, 2008; Moebius-Clune *et al.*, 2008; Stetson *et al.*, 2012) have found that the removal of the maize stover from the field reduces SOC content. This fact would explain the lower cumulative soil CO₂ emissions observed in NT compared with NTr and CT, in agreement with the results reported by Maris *et al.* (2018) for sprinkler-irrigated maize under Mediterranean conditions in which the maize stover was removed or incorporated to the soil by tillage operations. Therefore, the results presented in this work supported the initial hypothesis of greater soil CO₂ emissions for the conventional tillage under sprinkler irrigation.

Soil CH₄ fluxes measured in this work were in the range of values reported by Álvaro-Fuentes *et al.* (2016) for sprinkler-irrigated maize in Mediterranean areas. Throughout the entire measurement period, no significant differences in soil CH₄ fluxes between tillage systems were observed in any of the irrigation systems. Higher WFPS values measured under F irrigation, reaching values of 100% right after the water application, did not increase the CH₄ emissions. This fact could be related with the methanogenesis process, which requires strict anaerobic soil conditions. Moreover, a redox potential value (Eh) of -150 mV is considered as critical value for CH₄ production, being necessary a progressive reduction of the different soil electron acceptors O₂, NO₃⁻, Mn⁴⁺, Fe³⁺, SO₄²⁻ to reach this critical value of Eh (Wang *et al.*, 1993; Peters and Conrad, 1996). Likewise, the production of CH₄ soil can be inhibited by toxic effects (nitrite, NO₂⁻) and by competition for H₂ between denitrifiers and methanogens (Kluber and Conrad, 1998). Therefore, the short period in which the flood irrigation system presented values of WFPS close to 100% (first 24 h after the irrigation event) as well as the presence of an important amount of NO₃⁻ could explain the absence of CH₄ production events associated with the flood irrigation.

In general, over the three maize growing seasons and the two fallow periods, cumulative CH₄ emissions were negative, this meaning that soil acted as a CH₄ sink, as observed by Sanz-Cobena *et al.* (2014) under Mediterranean conditions. Methane consumption showed a trend to be greater under NTr, being 3.2 and 1.5 times higher compared with CT and NT tillage, respectively. These results were similar to those obtained by Pareja-Sánchez *et al.* (2019) in an irrigated maize field study under Mediterranean conditions, in which greater CH₄ uptake under no-tillage has been reported. Similarly, in soil core incubation experiments, Hütsch (2001) and Jacinthe *et al.* (2014) observed greater methanotrophic activity for agricultural soils under no-tillage. The increase in CH₄ uptake under no-tillage systems, especially for NTr treatments, could be related with the lower disturbance of the topsoil compared with tillage systems (Ussiri *et al.*, 2009). No-tillage systems may improve soil structure resulting in better soil gas diffusivity and an optimal circulation of gases throughout the soil profile, thus providing a more suitable condition for methane consumption (Ball *et al.*, 1999; Smith *et al.*, 2003; Ball *et al.* 2008). Given this, our initial hypothesis of greater CH₄ emissions under F irrigation was not supported by the observed results.

5. Conclusions

In this experiment, it has been observed that under Mediterranean conditions two important management practices (irrigation and tillage) have a significant impact on the soil carbon cycle. Specifically, over three maize growing seasons, both irrigation and soil tillage system affected soil CO₂ emissions, but not CH₄ emissions. More stable soil WFPS values provided by sprinkler irrigation system compared with flood irrigation favoured maize growth, thus leading to optimal conditions for the microorganism activity, and, ultimately, to greater soil CO₂ emissions compared with flood irrigation. Moreover, the incorporation into the soil of the maize stover by tillage operations increased the soil CO₂ emissions compared with the no-tillage systems. Soil CH₄ emissions were affected by the tillage system in one out of the two fallow periods, while the irrigation system did not impact on these emissions. Over the entire measurement period, soil acted as a sink of CH₄ with minimum differences between irrigation systems and a trend to greater CH₄ consumption under no-tillage systems.

The results of this work suggest that no-tillage maintaining the crop stover and sprinkler irrigation is a win-win strategy for irrigated maize under Mediterranean conditions, which results in lower soil CO₂ emissions and the maintenance of maize aboveground biomass yields, compared with conventional tillage and flood irrigated systems.

Acknowledgments

The authors would like to thank Elena Paracuellos Planas, César Romano, Miguel Ángel Millán Espiau, Valero Pérez Laguardia and Florin Ion for laboratory and field assistance. Samuel Franco-Luesma was awarded a FPI fellowship by the Ministry of Science, Innovation and Universities (MICINN) of Spain (ref. BES-2014-069175). Daniel Plaza-Bonilla was awarded a Juan de la Cierva postdoctoral grant by MICINN (refs. FJCI-2014-19570; IJCI-2016-27784). This research was supported by a MICINN grant (ref. AGL2013-49062-C4-4-R).

Declaration of Competing Interest

The authors declare no conflict of interest

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Figure captions.

Figure 1. Daily mean air temperature (black continuous line), precipitation (vertical bars) and reference evapotranspiration (ET_o) (grey continuous line) throughout the entire experimental period.

Figure 2. Soil water-filled pore space (WFPS) in the 0-5 cm depth for sprinkler (a) and flood (b) irrigation systems as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining the maize stover), NT (no-tillage removing the maize stover).

* Indicates significant differences between tillage treatments for a given date at $p < 0.05$.

Error bars represent standard error.

Figure 3. Soil temperature at 5 cm depth for sprinkler (a) and flood (b) irrigation systems as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining the maize stover), NT (no-tillage removing the maize stover). *Indicates significant differences between tillage treatments for a given date at $p < 0.05$. Error bars represent standard error.

Figure 4. Soil CO₂ flux for sprinkler (a) and flood (b) irrigation systems as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining the maize stover), NT (no-tillage removing the maize stover). *Indicates significant differences between tillage treatments for a given date at $p < 0.05$. Black triangles indicate fertilizer applications. White triangles indicate flood irrigation events. Error bars represent standard error.

Figure 5. Regression analysis between soil temperature (at 5 cm depth) and soil CO₂ fluxes as affected by soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover) and irrigation system (S, sprinkler irrigation; F, flood irrigation). Each point represents the average value for each sampling date.

Figure 6. Regression analysis between soil water-filled pore space (WFPS) (0-5 cm depth) and CO₂ fluxes as affected soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover) and irrigation system (S, sprinkler irrigation; F, flood irrigation). Each point represents the average value for each sampling date.

Figure 7. Cumulative CO₂ emissions for 2015, 2016 and 2017 growing seasons as affected by soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover) and irrigation system (S, sprinkler irrigation; F, flood irrigation). For each growing season, different letters indicate significant differences between treatments at $p < 0.05$.

Figure 8. Soil CH₄ flux for sprinkler (a) and flood (b) irrigation systems as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining the maize stover), NT (no-tillage removing the maize stover). Black triangles indicate fertilizer applications. White triangles indicate flood irrigation events. Error bars represent standard error.

Figure 9. Maize aboveground biomass for 2015, 2016 and 2017 growing seasons as affected by soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover) and irrigation system (S, sprinkler irrigation; F, flood irrigation). For each growing season, different letters indicate significant differences between treatments at $p<0.05$. Error bars represent standard error.

Figure 10. Regression analysis between cumulative soil CO₂ emissions and maize aboveground maize biomass. Each point represents the value of each tillage-irrigation treatments.

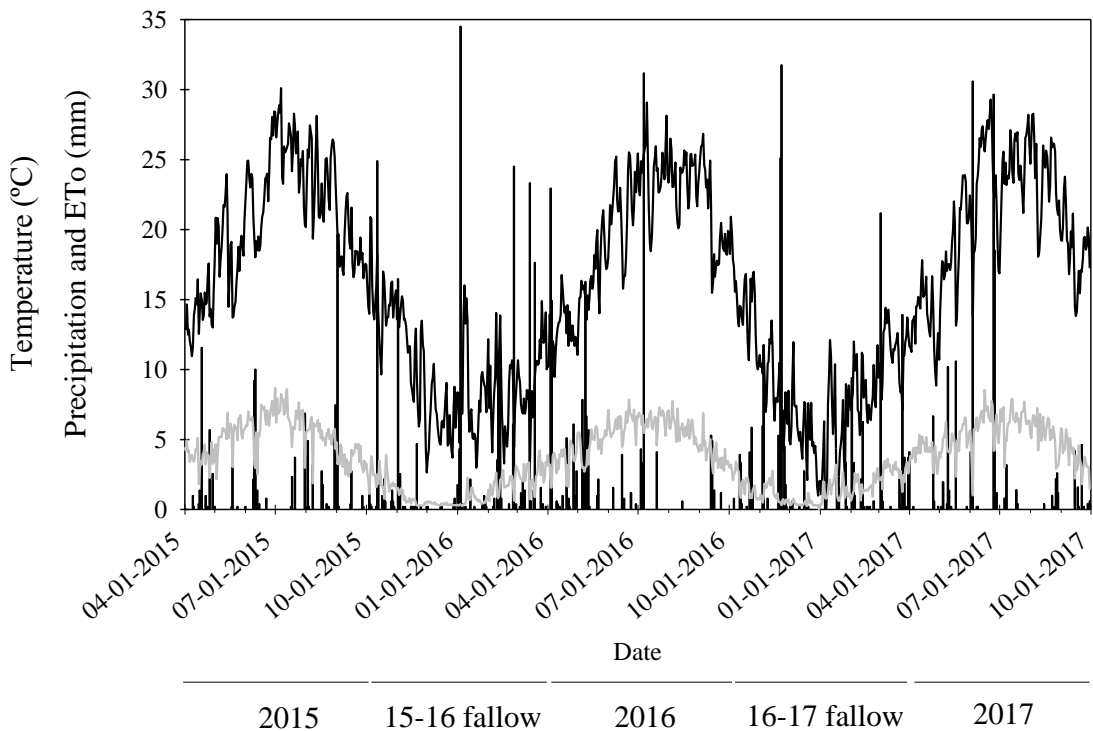


Fig. 1

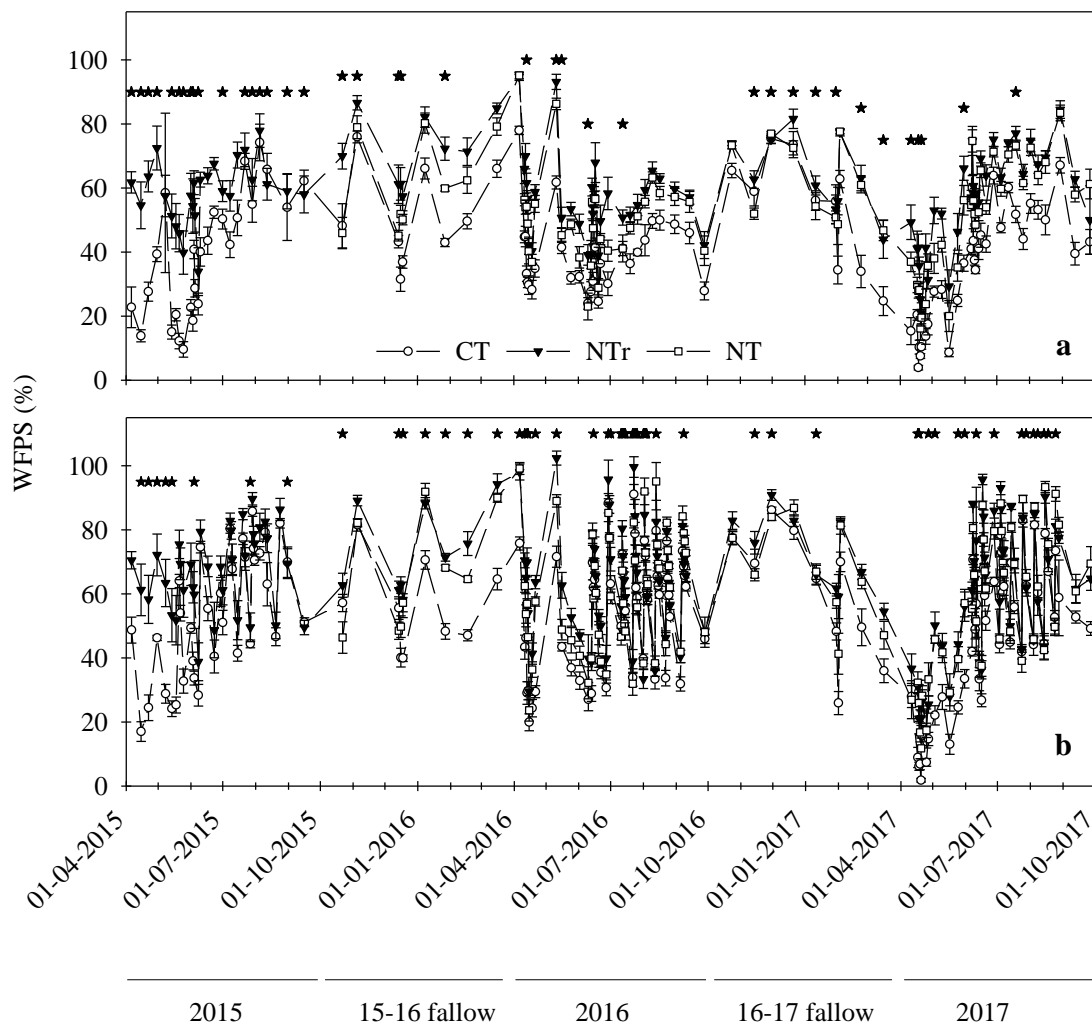


Fig. 2

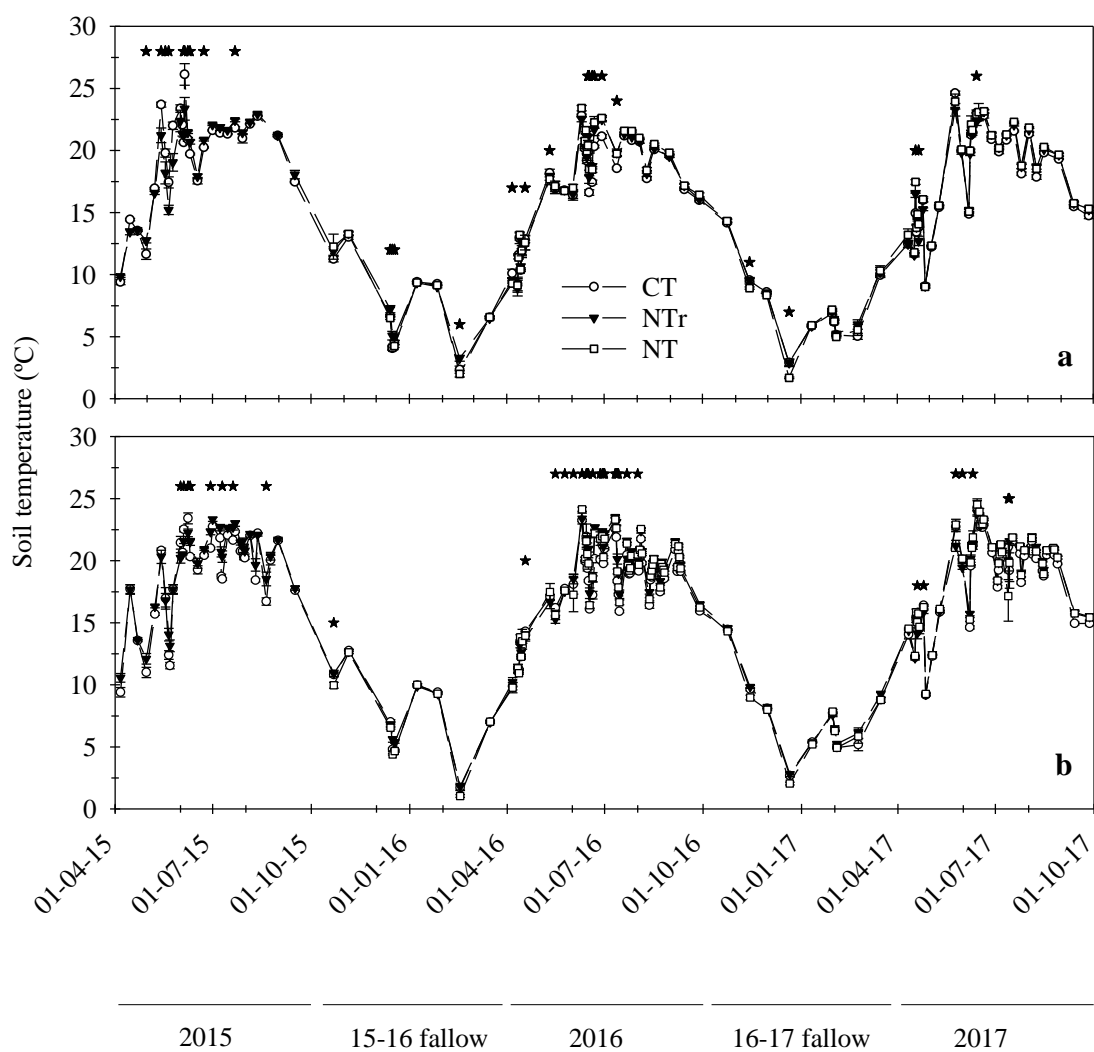


Fig. 3

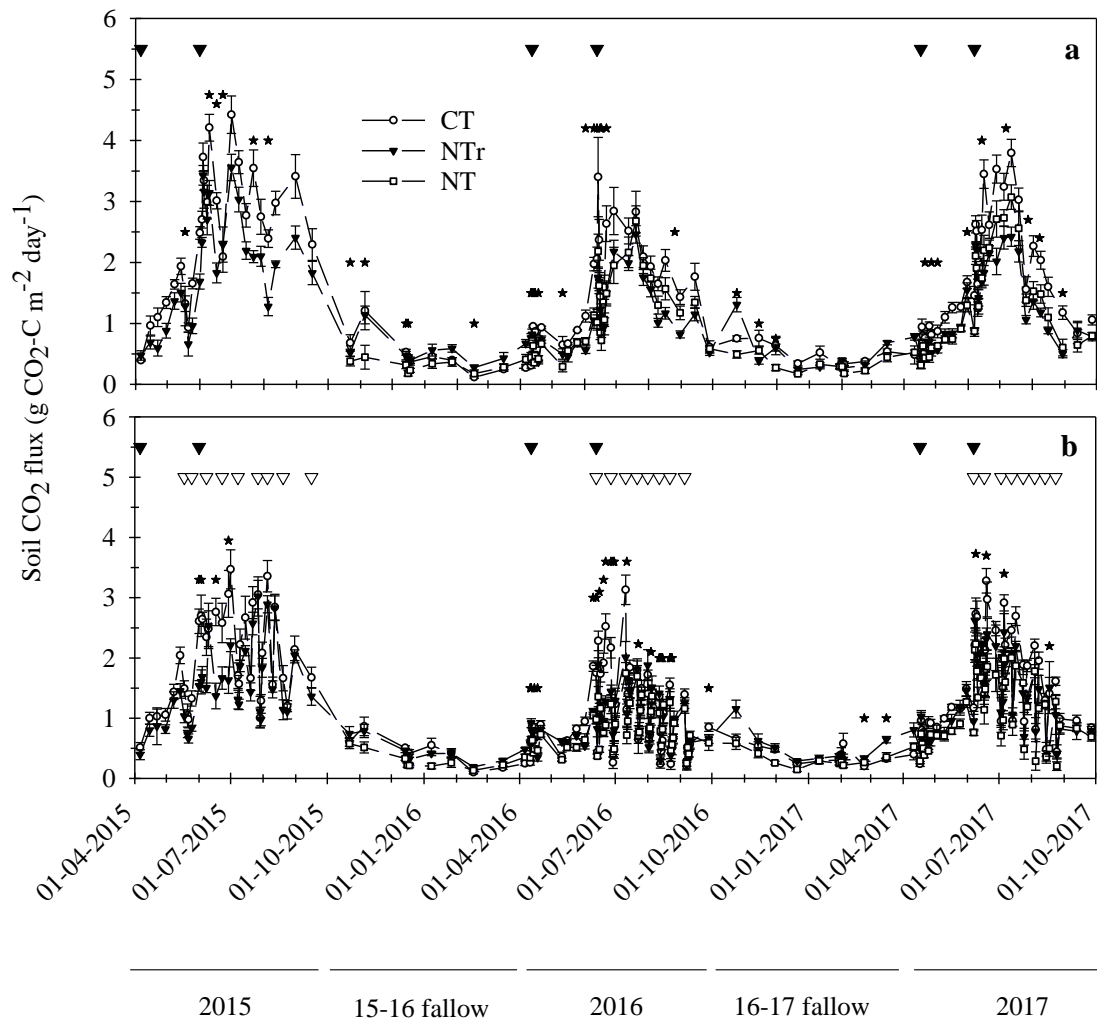


Fig. 4

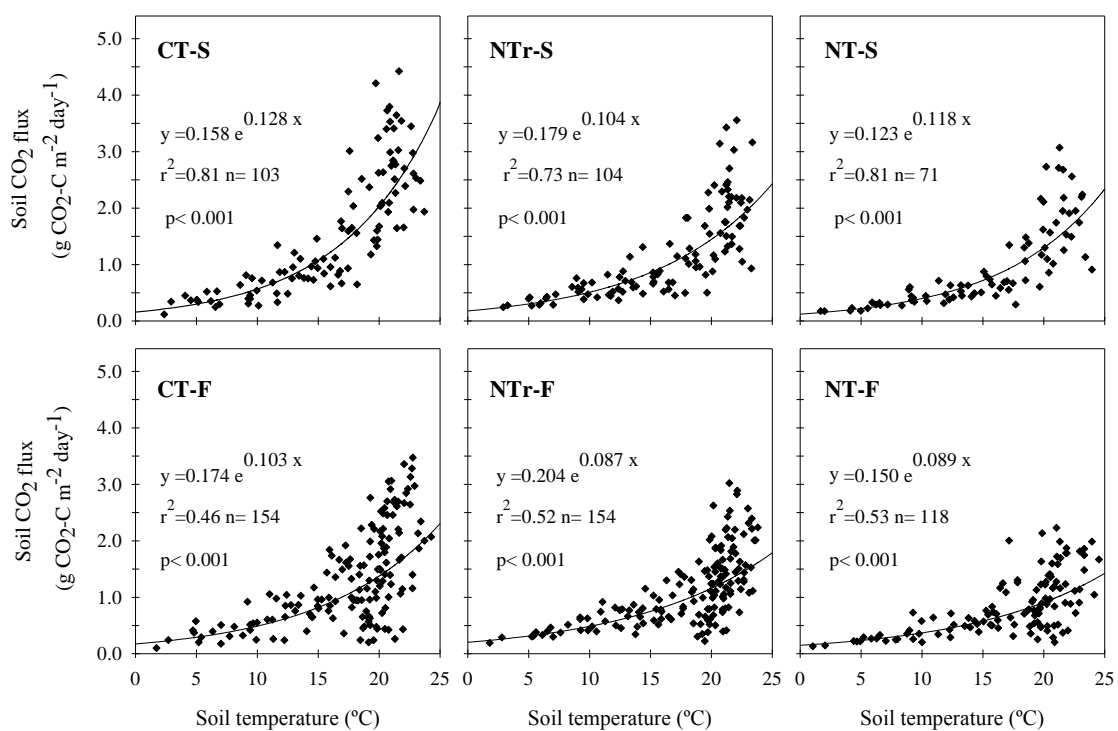


Fig. 5

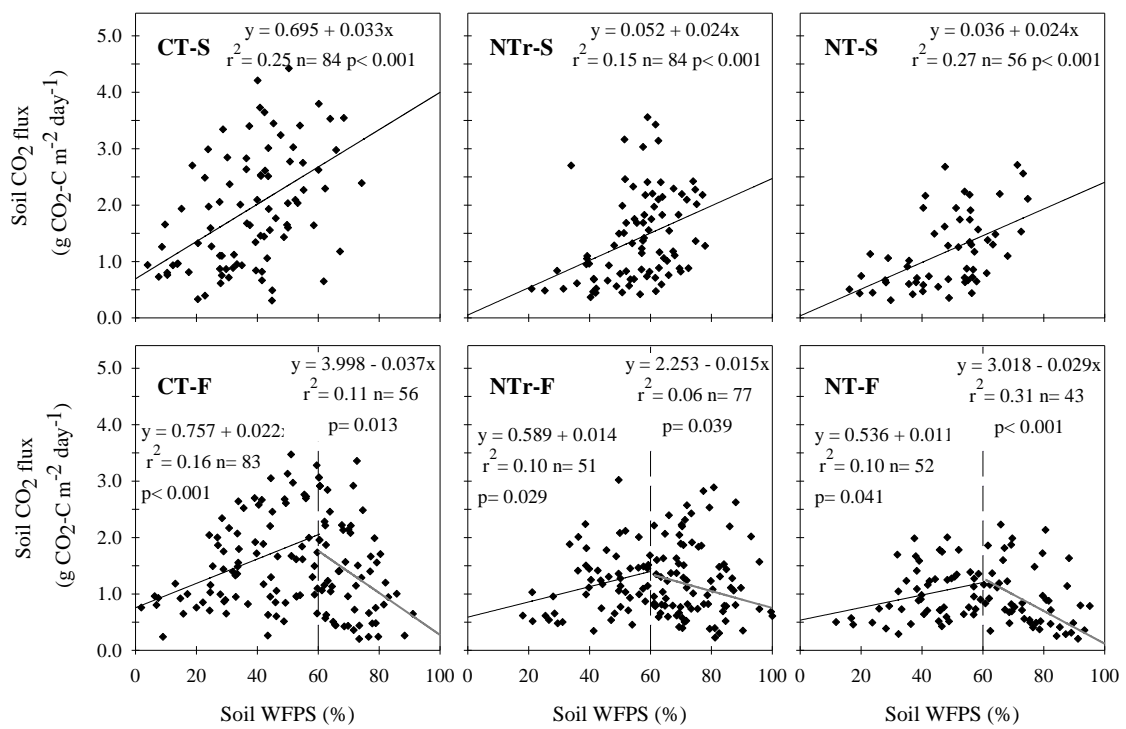


Fig. 6

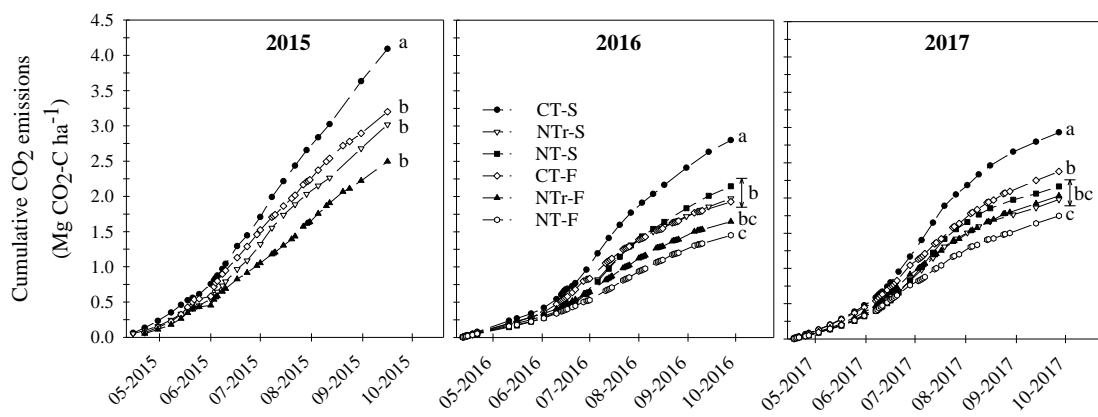


Fig. 7

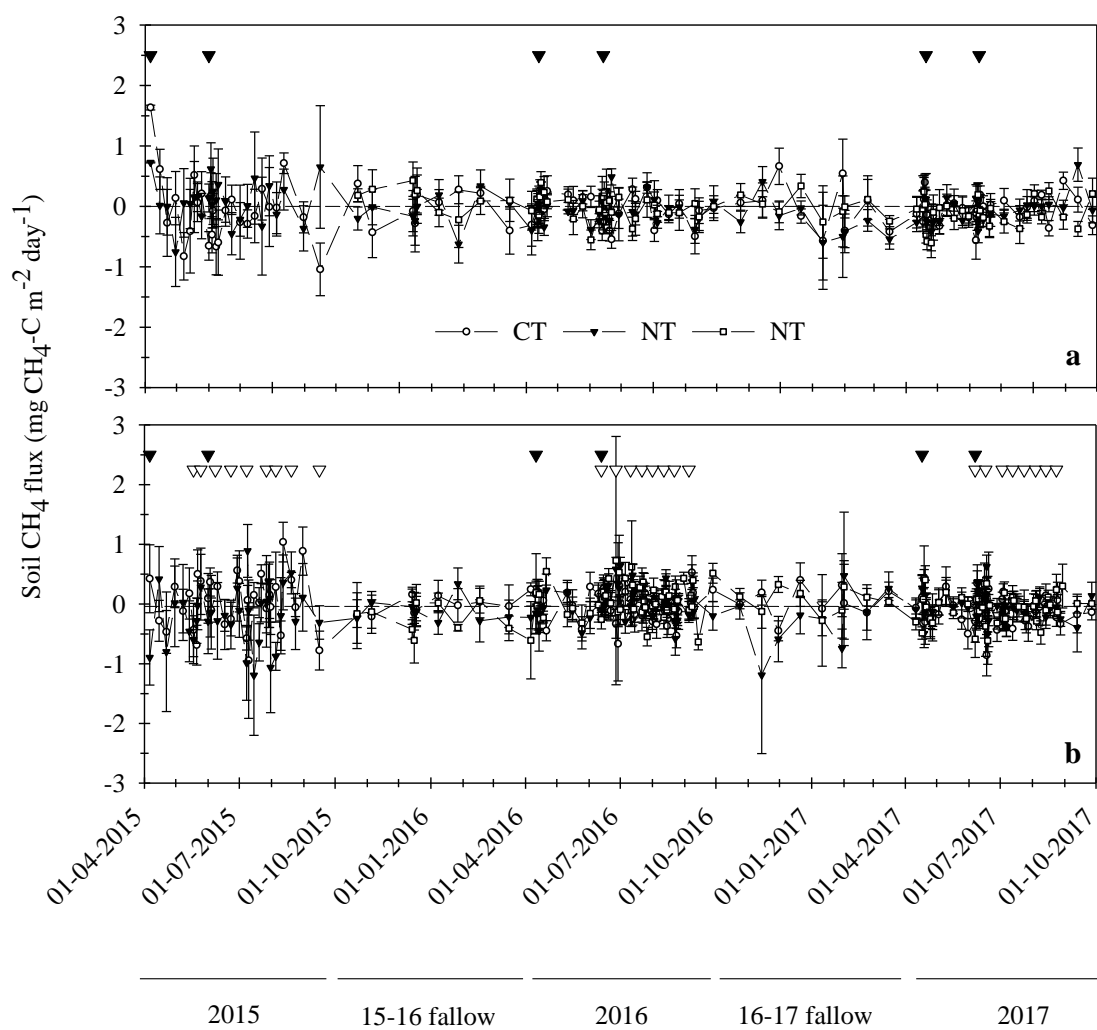


Fig. 8

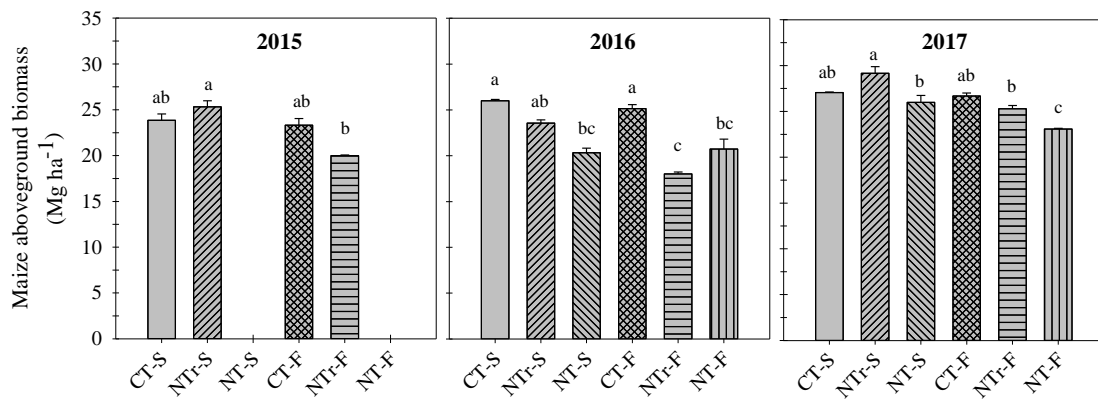


Fig. 9

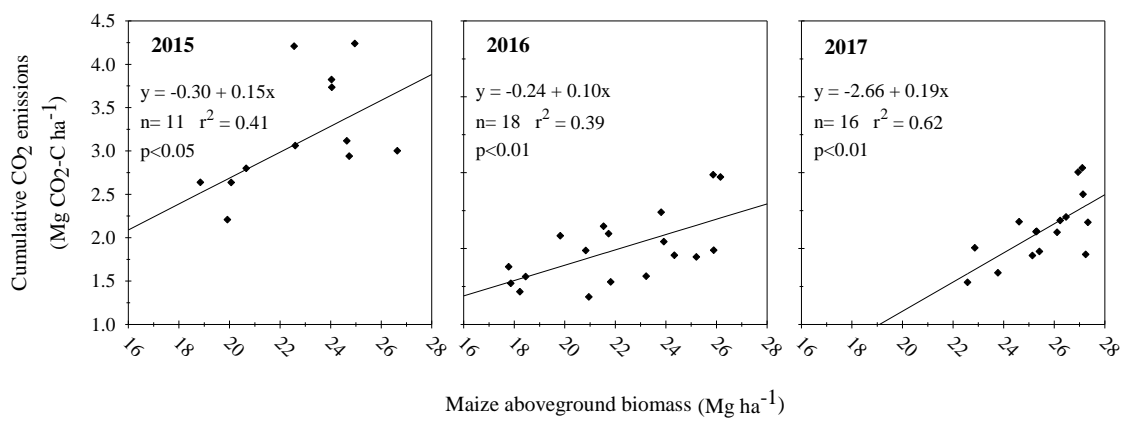


Fig. 10

Tables

Table 1. Soil characteristics at the beginning of the experiment.

Depth — (m) —	pH	SOC ^a	CaCO ₃	Sand (%)	Silt	Clay	FC ^b — (m ³ m ⁻³) —	WP ^c
0.00–0.05	7.98	1.93	34.9	15.7	61.9	22.4	0.26	0.14
0.05–0.10	8.20	1.85	34.9	15.4	62.9	21.7	0.26	0.14
0.10–0.25	8.03	1.75	35.1	15.9	62.1	22.0	0.25	0.16
0.25–0.50	7.95	1.51	35.3	16.1	63.6	20.3	0.25	0.16

^a Soil organic carbon. ^b Water content at field capacity (-0.033 MPa). ^c Water content at wilting point (-1.5 MPa).

738

739 Table 2. Schedule of field operations during the 2015, 2016 and 2017 maize growing seasons.

Field operation	2015	2016	2017
Stover management (NT)			
Stover removal		23/12/2015	11/11/2016
Tillage operation (CT)			
Subsoiler and disk harrow	11/03/2015	15/12/2016	31/01/2017
Rotary tiller	08/04/2015	12/04/2016	17/04/2017
No-tillage weed control (NTr; NT)			
Herbicide application	21/11/2014	11/04/2016	07/02/2017
Sowing (CT; NTr; NT)	09/04/2015	12/04/2016	17/04/2017
N Fertilization (CT; NTr; NT)			
Presowing application	08/04/2015	11/04/2016	17/04/2017
Top dressing application	02/06/2015	13/06/2016	07/06/2017
Harvest (CT; NTr; NT)	30/09/2015	05/10/2016	17/10/2017

740 (); For each field operation abbreviation inside brackets indicate in which soil tillage management was
741 performed it.

742

743

744 Table 3. Calculated crop evapotranspiration (ETc), precipitation, crop irrigation requirement (CIR) and
 745 irrigation water applied in both irrigation systems (sprinkler and flood) in 2015, 2016 and 2017 maize
 746 growing seasons.

Growing season	ETc	Precipitation	CIR	Irrigation	
				Sprinkler	Flood
mm					
2015	719	115	712	729	950
2016	763	130	722	708	824
2017	744	136	693	686	874

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749 Table 4. Analysis of variance *F* (F-value) and *P* (*p*-values) of soil water-filled pore space (WFPS) (0-5 cm)
 750 and soil temperature at 5 cm depth for sprinkler and flood irrigation and for 2015, 2016 and 2017 growing
 751 seasons and 15-16 and 16-17 fallow periods as affected by soil tillage, sampling date and their interactions.

Sprinkler irrigation										
Effects	2015		15-16 fallow		2016		16-17 fallow		2017	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
WFPS (%)										
Tillage	16.81	0.049	23.43	0.001	71.84	<0.001	7.45	0.047	64.16	<0.001
Date	32.80	<0.001	50.84	<0.001	22.68	<0.001	85.84	<0.001	102.4	<0.001
Tillage x Date	6.44	<0.001	2.97	<0.003	2.00	<0.001	3.61	<0.001	2.50	<0.001
Soil temperature (°C)										
Tillage	28.08	0.024	2.01	ns*	19.45	<0.001	1.02	ns	9.15	0.032
Date	186.5	<0.001	355.4	<0.001	661.9	<0.001	1136	<0.001	636.6	<0.001
Tillage x Date	8.78	<0.001	0.89	ns	2.18	<0.001	2.49	0.008	2.25	<0.001
Flood irrigation										
Effects	2015		15-16 fallow		2016		16-17 fallow		2017	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
WFPS (%)										
Tillage	14.76	ns	73.33	<0.001	38.85	0.002	17.77	0.01	76.15	<0.001
Date	22.59	<0.001	124.33	<0.001	106.9	<0.001	92.75	<0.001	184.9	<0.001
Tillage x Date	3.64	<0.001	6.58	<0.001	5.82	<0.001	2.45	0.008	2.07	<0.001
Soil temperature (°C)										
Tillage	0.25	ns	70.44	0.014	12.02	<0.001	19.79	<0.001	2.23	ns
Date	144.8	<0.001	1086	<0.001	230.6	0.021	1644	0.008	160.6	<0.001
Tillage x Date	4.19	<0.001	2.51	0.009	2.84	<0.001	2.83	0.003	2.63	<0.001

* ns, non-significant.

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Table 5. Analysis of variance of daily soil CO₂ and CH₄ fluxes for sprinkler and flood irrigation and for 2015, 2016 and 2017 growing seasons and 15-16 and 16-17 fallow periods as affected by soil tillage, sampling date and their interactions.

Sprinkler irrigation										
	2015 (n= 306)		15-16 fallow (n= 180)		2016 (n= 522)		16-17 fallow (n=198)		2017 (n= 558)	
	<i>Mean</i>	\pm <i>SE</i>	<i>Mean</i>	\pm <i>SE</i>	<i>Mean</i>	\pm <i>SE</i>	<i>Mean</i>	\pm <i>SE</i>	<i>Mean</i>	\pm <i>SE</i>
Tillage	Soil CO ₂ flux (g CO ₂ -C m ⁻² day ⁻¹)									
CT	2.50 a	0.09	0.48 ab	0.05	1.53 a	0.07	0.50 a	0.03	1.75 a	0.07
NTr	1.93 b	0.08	0.55 a	0.04	1.08 b	0.05	0.51 a	0.04	1.23 b	0.05
NT			0.32 b	0.03	1.12 b	0.05	0.35 b	0.02	1.30 b	0.06
Effects [†]	ANOVA									
Tillage	0.009		0.006		<0.001		0.042		0.027	
Date	<0.001		<0.001		<0.001		<0.001		<0.001	
Tillage x Date	0.008		<0.001		<0.001		0.002		0.002	
Tillage	Soil CH ₄ flux (mg CH ₄ -C m ⁻² day ⁻¹)									
CT	-0.10	0.07	-0.04	0.10	-0.05	0.03	-0.16	0.15	-0.05	0.02
NTr	0.06	0.08	-0.11	0.09	-0.05	0.03	0.06	0.12	-0.05	0.03
NT			0.11	0.09	-0.01	0.02	0.19	0.15	-0.11	0.03
Effects	ANOVA									
Tillage	ns*		ns		ns		ns		ns	
Date	ns		ns		ns		ns		ns	
Tillage x Date	ns		ns		ns		ns		ns	
Flood irrigation										
	2015 (n= 426)		15-16 fallow (n= 180)		2016 (n= 972)		16-17 fallow (n=198)		2017 (n= 826)	
	<i>Mean</i>	\pm <i>SE</i>	<i>Mean</i>	\pm <i>SE</i>	<i>Mean</i>	\pm <i>SE</i>	<i>Mean</i>	\pm <i>SE</i>	<i>Mean</i>	\pm <i>SE</i>
Tillage	Soil CO ₂ flux (g CO ₂ -C m ⁻² day ⁻¹)									
CT	2.00	0.06	0.43 a	0.02	1.06	0.04	0.40 ab	0.03	1.56 a	0.05
NTr	1.55	0.05	0.45 a	0.03	0.95	0.03	0.53 a	0.03	1.36 ab	0.04
NT			0.31 b	0.02	0.84	0.02	0.33 b	0.02	1.14 b	0.03
Effects	ANOVA									
Tillage	ns		0.011		ns		0.01		0.014	
Date	<0.001		<0.001		<0.001		<0.001		<0.001	
Tillage x Date	0.008		ns		<0.001		0.008		0.026	
Tillage	Soil CH ₄ flux (mg CH ₄ -C m ⁻² day ⁻¹)									
CT	0.02	0.07	0.02	0.09	-0.03	0.02	0.02	0.11	-0.11	0.03
NTr	-0.19	0.08	-0.11	0.08	0.02	0.03	-0.44	0.22	-0.05	0.02
NT			-0.26	0.10	0.08	0.05	-0.08	0.20	-0.06	0.03
Effects	ANOVA									
Tillage	ns		ns		ns		ns		ns	
Date	ns		ns		ns		ns		ns	
Tillage x Date	ns		ns		ns		ns		ns	

[†]For each variable, measurement period and effect, values followed by different letters are significantly different according to Tukey test at $p=0.05$ level. * ns, non-significant.

Table 6. Analysis of variance *F* (F-value) and *P* (*p*-values) of cumulative soil CO₂ emissions, cumulative soil CH₄ emissions and total aboveground maize biomass for 2015, 2016 and 2017 growing seasons and 15-16 and 16-17 fallow periods as affected by irrigation system, tillage system and their interactions.

Effects and levels	2015		15-16 fallow		2016		16-17 fallow		2017	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Cumulative soil CO ₂ emissions										
Irrigation system	60.37	0.004	1.58	ns	20.07	0.011	9.21	ns	3.84	ns
Tillage system	50.81	0.006	28.16	<0.001	68.95	<0.001	20.91	0.002	106.5	<0.001
Irrigation x Tillage	22.03	0.04	2.07	ns	12.69	0.003	4.03	ns	17.65	0.001
Cumulative soil CH ₄ emissions										
Irrigation system	2.14	ns*	0.19	ns	1.22	ns	1.89	ns	1.05	ns
Tillage system	0.71	ns	1.39	ns	0.56	ns	1.6	0.025	0.65	ns
Irrigation x Tillage	4.03	ns	0.38	ns	0.32	ns	0.45	ns	0.35	ns
Total aboveground maize biomass										
Irrigation system	18.3	0.024			30.74	0.003			33.07	0.009
Tillage system	2.59	ns			33.47	<0.001			24.03	0.001
Irrigation x Tillage	15.58	0.029			7.92	0.013			8.62	0.015

* ns, non-significant.